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Deadbeat Controller based Transformerless Inverter for Grid Tied PV System with Reactive Power Control

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***Abstract*—This paper presents a single phase transformerless inverter for grid-tied PV system with reactive power control. Inverters with transformers of the conventional type, which connected in PV grid-tied systems are being replaced by transformerless inverters due to various reasons such as reduction in size, weight and cost, improvement in efficiency etc. Transformerless inverters cause a number of technical problems in grid-connected PV systems, among which flow of leakage currents is a major problem. This leakage current that flows between the parasitic capacitance of PV array and the grid has to be eliminated, may otherwise leads to major safety problems. However, one of the technical challenges of the transformerless inverter is the safety issue of leakage current. In addition, according to the international regulations, transformerless inverter should be capable of handling a certain amount of reactive power.Here, a new transformerless inverter for grid-tied PV system is proposed which can eliminate the threat of leakage current. The proposed topology also have the ability to inject reactive power into the utility grid. Besides a maximum power point tracker (MPPT) using the P & O algorithm in the system ensures optimal power of the PV array in use. A PR controller and a dead-beat current controller are used to ensure high quality injected current to the grid. Detailed analysis of proposed transformerless inverter with operation modes, commonmode leakage current analysis and reactive power control capability in MATLAB simulation model are presented.**

Keywords*— Grid connected photovoltaic systems,MPPT, transformerless inverter, parasitic capacitance, common mode voltage, leakage current, Dead beat current control.

1.INTRODUCTION

Photovoltaicinverters become widespread within both private and commercial circles.These grid-connected inverters convert the available direct currentsupplied by the PV panels and feed it into the utility grid[1].There are two main topology groups used in the case of grid-connected PV systems, namely, with and without galvanicisolation [2]. Galvanic isolation can be on the dc side in theform of a high-frequency dc–dc transformer or on the gridside in the form of a big bulky ac transformer. Both of thesesolutions offer the safety and advantage of galvanic isolation,but the efficiency of the whole system is decreased due to powerlosses in these extra components. In case the transformer isomitted, the efficiencyof the PV system can be increasedwith an extra 1%–2%.

Single phase-PV grid connected systems present suitable solution for small PV systeminstallations. The PV generates direct voltage; thus, it requires a converter to convert into a voltage of corresponding amplitude at mainfrequency for feeding it into utility grid. However, the problemcan arises because of the hazardous voltage that can be avoided byproviding galvanic isolation between the PV module and the gridthrough a transformer [3,4]. Nevertheless, the use of a transformerleads to additional drawbacks such as less efficiency, bulky, moreexpansive and less durability. In order to overcome thesedrawbacks, transformerless inverter has been introduced which hasthe benefits such as lower cost, higher efficiency, smaller size andweight [3,5].Owing to the missing galvanic separation, large voltage fluctuation both at main frequency and high frequency thatdepends on the topology structure and control scheme, resulted inleakage current flow from the PV module to the system throughthe inevitable parasitic capacitance with respect to ground potential[6]. This ground leakage current increases the grid currentharmonics and system losses and also creates a strong conductedand radiated electromagnetic interference [7,8].

Transformerless PV inverters use different solutions to minimize the leakage ground current and improve the efficiency ofthe whole system[9,10].The PV array parasitic capacitance between the PV array and the ground causes leakage current toflow..Many PV inverter topologieswith different switching strategies have been proposed to mitigate theproblem of common-mode voltage (CMV) andground leakage current.

An important aspect related to the photovoltaic system connected to the electric grid is that it can operate the doublefunctions of active power generator and reactive power compensator. The proper power factor is selected accordingto active power and reactive power that the grid demands.

Two current controller are developed for this single phase grid tied transformerlessinverter: The PR current controller and the deadbeat current controller. The current controller takescare of the quality ofcurrent injected into the grid and the power exchange betweenthe system and grid.

Proportional + Resonant (PR) current controller which maintains the current injected by the inverter into grid in phasewith the grid voltage so that unity power factor can be achieved.A harmonic compensator (HC) is cascaded with PR controller tomitigate low order odd harmonic components present in theoutput current of VSI and minimize the total harmonic distortion(THD).loop. In stationary or α-β frame control structure the control variables are time varying. The Proportional Resonant (PR)controllers falls under the category of stationary framecontrollers are simple to design and has excellent referencesignal tracking capabilities. The PR controllers can achieve every high gain at resonant frequency thus reducing the steadystate error to zero [11-13]. More over harmonic compensatorscan be used to mitigate low order harmonic withoutinfluencing behavior of the current controller. Hence they aresuperior than PI controllers in terms of eliminating steady stateerrors and harmonic current rejection.A deadbeat current controller is also implemented for single phase PV grid connectedinverters. They used a control method based on a discrete-time model of the system in order to produce the invertervoltage for good tracking of the current reference.

To synchronize the photovoltaic system output and the ACgrid a PLL (phase-locked loop) was implemented.An L filter or LCL filter is usually placed between the inverter and the grid to attenuate the switching frequency harmonics produced by the grid-connected inverter. Compared with L filter, LCL filter has better attenuation capacity of high-order harmonics and better dynamic characteristic [14,15].MPPT controller is designed toestimate the output voltage and current from the PV array andextract maximum power from the source.

In this paper, a newtransformerless inverter topology for grid tied PV system is developed.In Section II,proposed PV transformerless inverter topology is presented.InSection III,Common-mode voltage and leakage current analysis in transformerless PV Inverter is shown. InSection IV, the control methods ofthe proposed topology are described. Section V presents the simulation results of proposed topologies with real and reactive power control using PR controller and Deadbeat controller.

II. PROPOSED PV TRANSFORMERLESS INVERTER TOPOLOGY

The proposed transformerless PV inverter, which is composed of six MOSFETs switches (S1–S6), six diodes (D1–D6),and inductors *L*1 and *L*2 as shown in Fig.1. The diodes D1–D4 perform voltage clampingfunctions for active switches S1–S4.The ac-side switch pairs are composed of S5, D5 and S6, D6, respectively, which provide unidirectional current flow branches during the freewheeling phases decoupling the grid from the PV array and minimizing the CM leakage current.

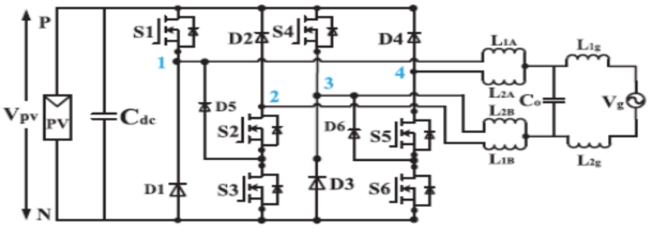


Fig.1.Proposedtransformerlessinverter

Fig. 2 shows the gate drive signal for the proposed circuit structure. It can be seen that a phase shift is occurred between the voltage and current.The proposed transformerless inverter operates in four stages within a grid period.

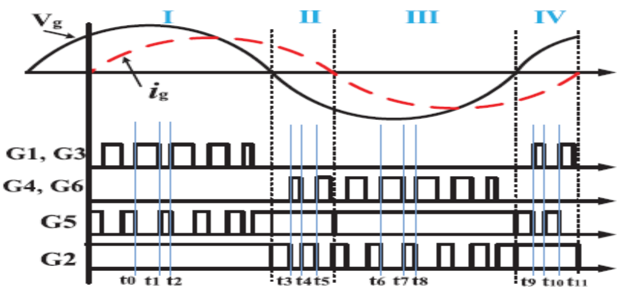


Fig.2 Gate signal of proposed transformerless inverter

Stage 1: This is the positive power region in the positive half-cycle of grid current. In this stage, S2 is always on, whereasS1 and S3 synchronously and S5 complementary commutate withswitching frequency. The generated output voltage are + VPV and 0.

Stage 2: This is negative power region in positive half-cycle of the grid current. In this stage, the inverter output voltageis negative but the current remains positive.The generated output voltage are −VPV and 0.

III LEAKAGE CURRENT ANALYSIS FOR THE PROPOSED TRANSFORMERLESSINVERTER

A galvanic connection between the ground of the grid and the PV array exists in transformerless grid-connected PVsystems. Large ground leakage currents may appear due to the high stray capacitance between the PV array and theground.To analyze the ground loop leakage current, Figure shows a model with the phase output points 1, 2, 3,and 4modeled as controlled voltage sources connected to the negative terminal of the dc bus.

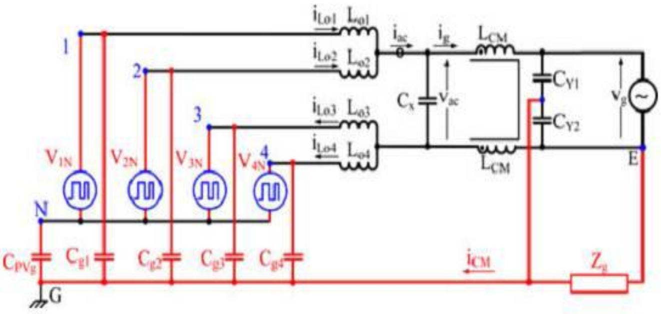


Fig.3 Leakage current analysis model

Fig.3 clearly shows the elementsthat influencing the ground leakage current, which include:

1) The stray capacitance between PV array and ground C_{PVg};

2) Stray capacitances between the inverter devices and the ground Cg1 – Cg4 and

3) The series impedance between the ground connection points of the inverter and the grid Zg.

The differential-mode (DM) filter capacitor *Cx*and the filter components L_{CM}, C_{YI}, and $C_{Y2}$are also shown in the model. The value of stray capacitances *Cg1*, *Cg2*, *Cg3*, and *Cg4* of MOSFETs is low compared with that of Cpv_g,,therefore the influence of these capacitors on leakage current can be neglected. It is also noticed that the DM capacitor *Cx*does not affect the CM leakage current.Hence the controlled voltage sources *V*2N and V4N are equal to zero and can be removed.

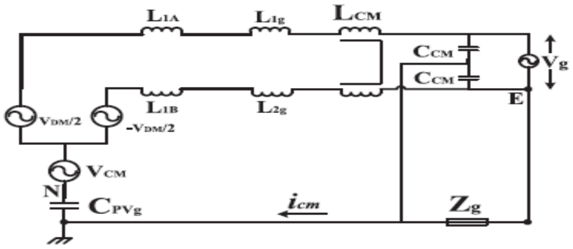


Fig.4 Simplified CM Leakage current analysis for positive half cycle

A simplified CM leakage current analysis for the positive half-line cycle is presented in fig.4. a single-loop mode applicable to the CM leakage current analysis for the positive half-line cycle of the proposed transformerless inverter is obtained.

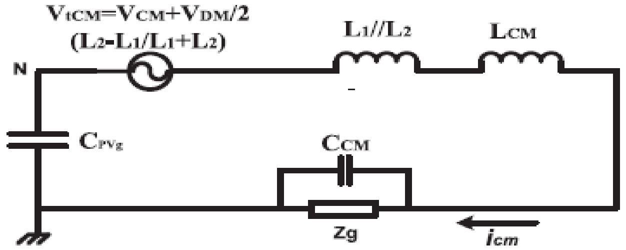


Fig.5 Simplified single loop CM model

Common mode voltage,

$$V_{CM} = \frac{V_{1N}+V_{3N}}{2} \qquad (1)$$

Differential mode voltage,

$$V_{DM} = V_{1N} - V_{3N} \qquad (2)$$

Total common mode voltage,

$$V_{tCM} = \frac{V_{dc}}{2} \qquad (3)$$

It is clear that if the total CM voltage Vt$_{CM}$ keeps constant, no CM current flows through the converter. For a well designedcircuit with symmetrically structured, normally *L*$_{01}$is equal to *L*$_{03}$. During the active stage of the positive halflinecycle, *V*1N is equal to *V*dc, while V3N is equal to 0. Similarly, during the whole negative half-line cycle, the CMleakage current mode is exactly the same as the one during the positive half-line cycle; the only difference is the activation of different devices. The total CM voltage in negative half cycle is also equal to *V*dc/2.

IV CONTROLLER DESIGN FOR SINGLE PHASE GRID TIEDTRANSFORMERLESS INVERTER

Two controllers are developed for the single phase grid tied inverter: the PRcontroller and the deadbeat controller. The current controller takes care of the quality ofcurrent injected into the grid and the power exchange between the system and grid.$I_{g\alpha}^{ref}$ which is in phase with the grid voltage controls the real power of the system and the orthogonal component $I_{g\beta}^{ref}$ controls the reactive power exchange of the system with the grid. Hence a decoupled control of real and reactive power can be achieved.

A. Proportional Resonant Current Controller

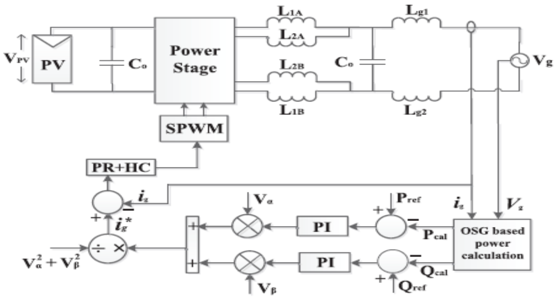


Fig.6. Block diagram of control of proposed system with PI controller

The PR controller is used in the stationary frame unlike the PI controller. The computationsequence of the PR controller is not complex because there is no transformation from the stationaryframe to synchronous frame. For these reasons, a low-cost processor can be used.In addition, whengrid unbalance or a sensing error occurs, the PR controller is more robust than the PI controller.Especially, the PR controller is suitable for constant frequency operation in the grid-connected system.

Generally, the PI controller has drawbacks such as difficulty in removing the steady-state error in a stationary reference frame. The PR controller structure recently gained considerable popularity owingto its capability of eliminating steady-state error when regulating sinusoidal signals.Moreover, the easy implementation of a harmonic compensator without any adverse effect on thecontroller performance makes this controller well suited for grid-tied systems. Figure 6 shows block diagram of PR controller. The transfer function of the PR controller is defined below:

$$G_C(S) = K_{pi} + K_{ii} * \frac{s}{s^2+w_f{}^2} \qquad (4)$$

$$G_h(s) = \sum\nolimits_{h=3,5,..} \frac{K_{ih}s}{s^2+hw_f{}^2} \qquad (5)$$

$$G_d(s) = \frac{1}{1+1.5T_S S} \qquad (6)$$

Where*Kpi*and*Kii*are the proportional and resonant gain, *ωf*is the fundamental frequency, *Kih*is the resonant gain at the nthorderharmonic, *h* is the harmonic order, and *Ts*is the samplingperiod.

B. Deadbeat current Controller

In deadbeat control algorithm,state space model of the system is used to calculate the require reference value of current in order to reach the desired value for loadcurrent.Itis defined as at the beginning of each sampling period collect input current of PWM rectifier,then predict input current value *iref*for next sampling instant through calculation.

Cost function *J*=*i*-*iref*and our aim is to make sure *i*-*i** for beginning of next sampling period.

In the generation of dead beat current control ,reference current is calculated based on the fact that the predicted value of filter current should be same as reference value of filter current. Predicted value of filter current from, is given as following:

$$i_{fi}(k+1) = G_{11}V_{fc}(k) + G_{12}i_{fi}(k) + H_{11}\mu_c(k)$$

$$+H_{12} i_{ft}(k) \qquad (7)$$

Cost function (J) is defined to minimize the error between predicted value of filter current and reference value of current. Predicted value of reference current is calculated using, second order Lagrange's extrapolation:

$$i_{fi}(k+1) = 3i_{fi}*(k) - 3i_{fi}*(k-1) + i_{fi}*(k-2) \qquad (8)$$

The deadbeat current control equation is given by:

$$\mu_c*(k) = \frac{i_{fi}*(k+1) - G_{11}V_{fc}(k) - G_{12}i_{fi}(k) - H_{12}i_{ft}(k)}{H_{11}} \qquad (9)$$

Most known type of predictive controller use is dead beat controller .The model of the system is used to calculate the required reference value in order to reach the desired input signal. Modulation is then operated by comparing the carrier signal with the reference signal. The control for gate signal is generated from the different type of modulation.

The system parameters are listed in Table I.

TABLE I
SYSTEM PARAMETERS

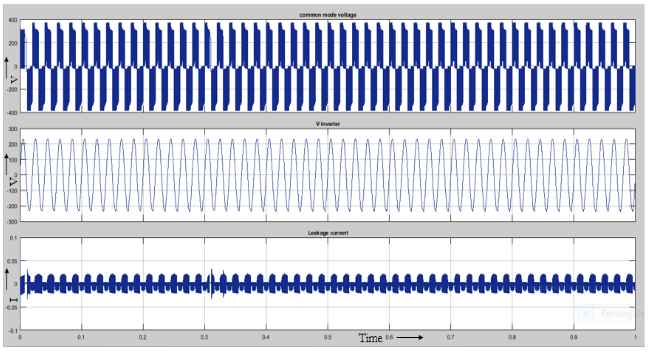
PARAMETERS	Values
Input voltage	400 Vdc
Grid voltage/frequency	230V/50 Hz
Swithching Frequency	20KHz
Filter Inductor	1 mH
L_{1A},L_{1B},L_{2A},L_{2B}	0.5 mH
Filter Inductor L_{g1},L_{g2}	75 nF
PVParasitic Capacitor	
C_{PV1},C_{PV2}	

V.SIMULATION RESULTS

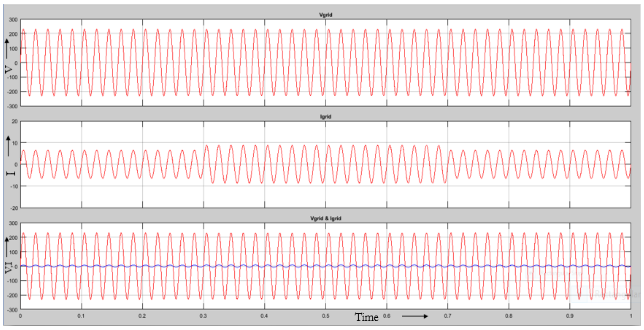
The simulation of transformerless PV inverters was performed using the MATLAB SOFTWARE . In this section, comparison of different parameters such as inverter voltage, common mode voltage (CMV), leakage current, grid voltage, grid current and the performance of proposed topology under changes of active and reactive power are discussed. PR current controller and Deadbeat current controller are analyzed to compare their control performances. In the simulation using PR controller, two cases are considered:

1) Case I: Performance of the proposed topology with PR Controller under the changes of active power only.

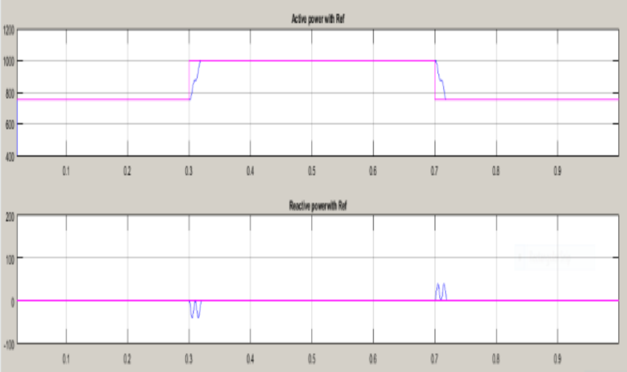
2) Case II: Performance of the proposed topology with PR Controller under the changes of active power and reactive power.



(a)

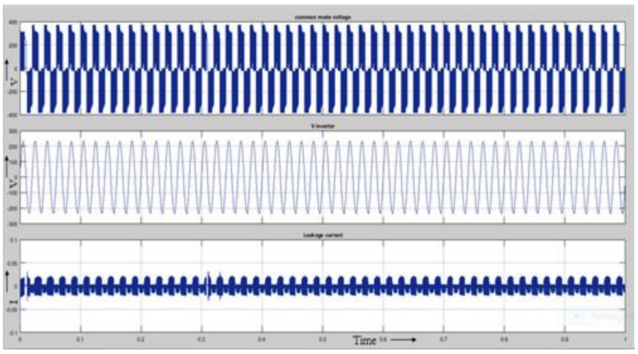


(b)

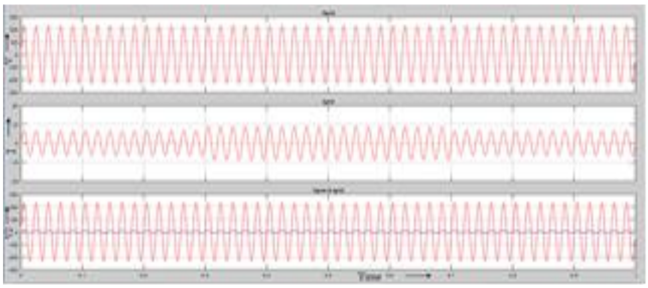


(c)

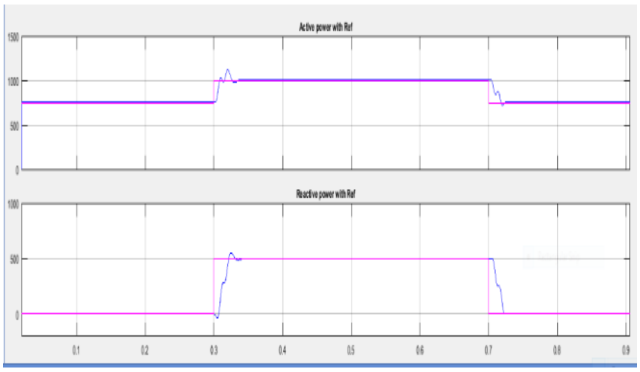
Fig. 7. Simulation results using PR controller with Active Power Control only:(a)Commonmodevoltage(v),Inverter voltage(v),Leakage current(A) (b) Grid Voltage(v),Grid Current (A)and (c)Active Power with Reference(W),Reactive Power with Reference(VAR)



(a)



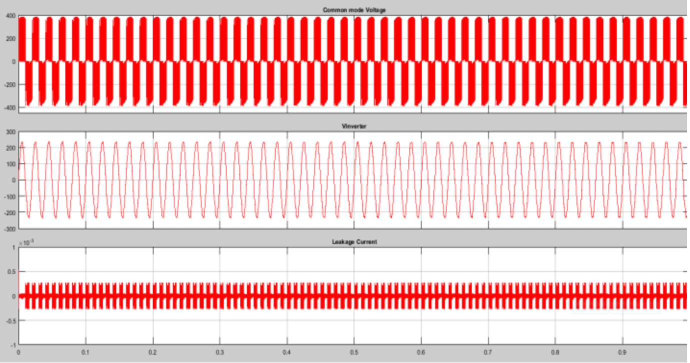
(b)



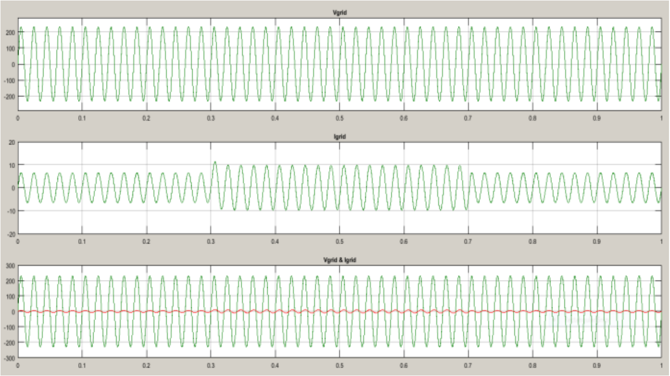
(c)

Fig. 8. Simulation results using PR controller with Active Power and Reactive Power Control:(a)Commonmode voltage(v),Inverter voltage(v),Leakage current(A) (b) Grid Voltage(v),Grid Current (A)and (c)Active Power with Reference(W),Reactive Power with Reference(VAR)

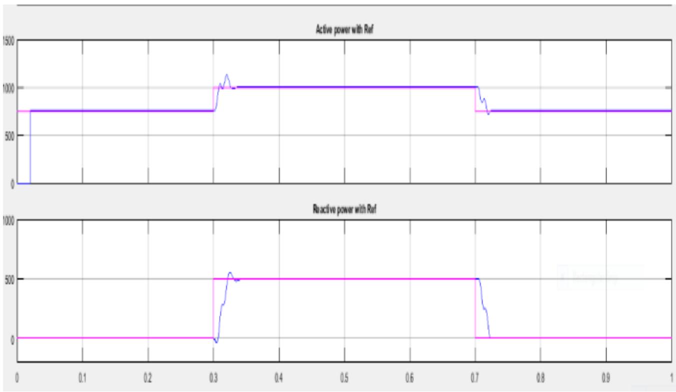
In the simulation using Deadbeat controller,Performance of the proposed topology under the changes of active power and reactive power is as follows:



(a)



(b)



(c)

Fig. 9. Simulation results using Deadbeat controller with Active Power and Reactive Power Control:(a)Commonmodevoltage(v),Invertervoltage(v),Leakage current(A) (b) Grid Voltage(v),Grid Current (A)and (c)Active Power with Reference(W),Reactive Power with Reference(VAR)

Fig. 7 shows the simulated results of proposed topology using PR controller with active power control only. The waveforms of the grid voltage vg and grid current ig are pure sinusoidal and achieved unity power factor.In the response of the system when it is subject to 750W load to 1000W load step change,it can clearly be seen that fast and effective response under the changes of active power reference are achieved with the proposed topology.Therefore, it can be concluded that the proposed topology can inject real power into utility grid with low leakage current.

Fig. 8 shows the simulated results of proposed topology using PR controller with active power and reactive power control.In the waveform of grid current ig and grid voltage vg for inductive power generation ,it is noticeable that no extra distortion is occurred in grid current when inject reactive power.In the response of the system when it is subject to 750W load to 1000W load step change,it can clearly be seen that fast and effective response under the changes of active and reactive reference power are achieved with the proposed topology.Therefore, it can be concluded that the proposed topology can inject reactive power into utility grid with low leakage current.

Fig. 9 shows the simulated results of proposed topology using Deadbeat controller with active power and reactive power control.The leakage current in deadbeat controller is very small compared to PR controller and it's value is only 0.025 mA.Also, in deadbeat controllerthe active and reactive power controller track the reference power within two cycle of operation while in PR controllerthe active and reactive power controller track the reference power within four cycle of operation.

CONCLUSION

This study proposesa high efficiency transformerless Inverter for PV grid-connected power generation systems with reactive power control. The simulated results using PR controller and deadbeat controller are compared.Furthermore, the proposed topology has the following advantages:

1.The proposed topology has the ability to inject reactive power into utility grid with low harmonic distortion.

2.The CM mode voltage is kept constant during the whole grid period even when inject reactive power into utility grid; thus, theleakage current is well suppressed.

3. High efficiency can be achieved by employing super junction MOSFETs for all switches. For high inverter efficiency, higher switching frequency (20 KHz) operation is allowed to reduce the output current ripple and the size of passive components.

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